Health Management Issues and Strategy for Air Force Missiles

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Agenda

- Introduction
- Background on Solid Rocket Motors
- Implementation of IVHM for Solid Rocket Motors
  - Past development and current application
  - Future challenges and needs
  - Model for implementation on future systems
- Wish list for future capabilities
- Conclusions

Introduction

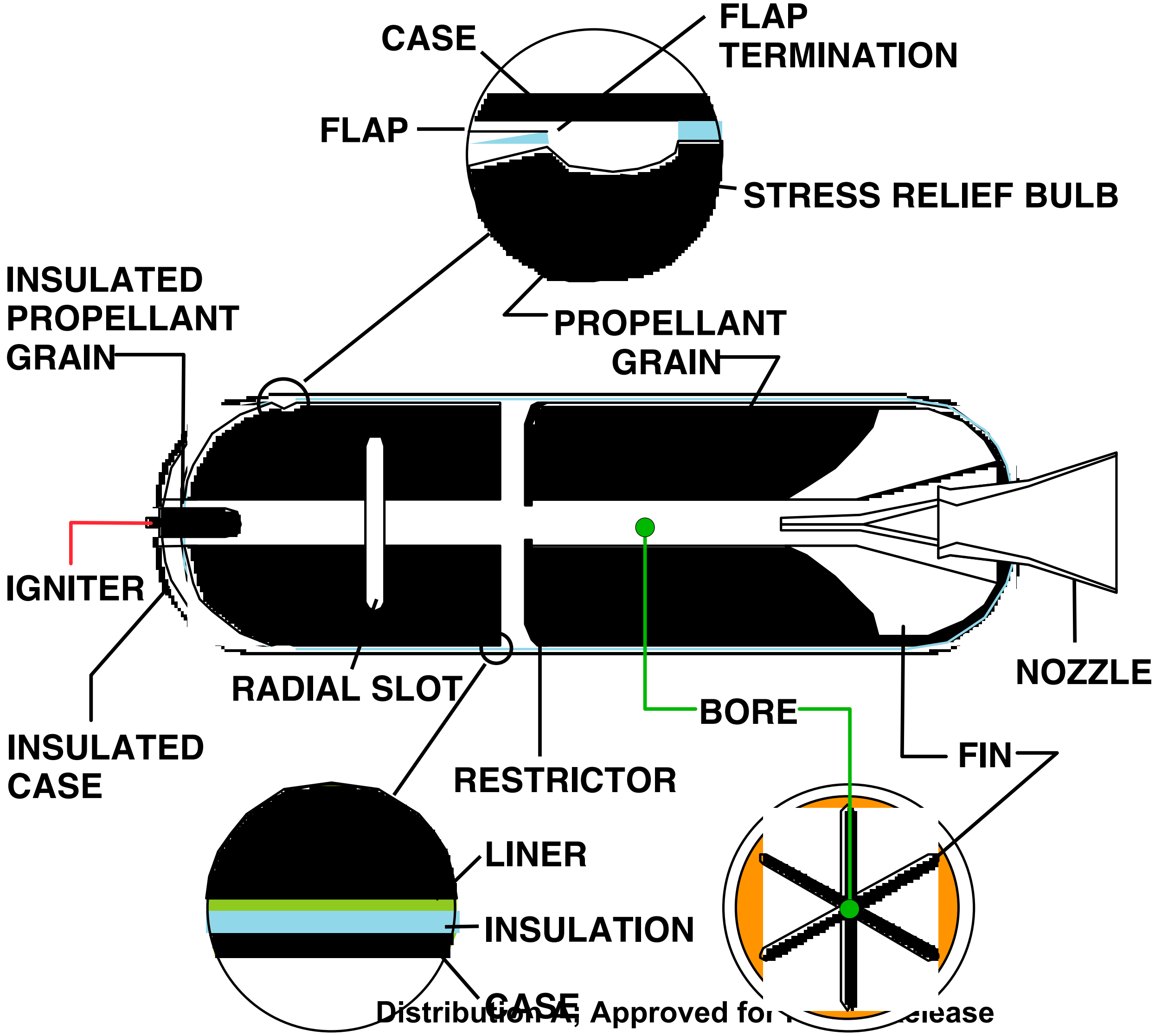
- **Air Force missiles are considered to be "wooden rounds"**
  - Must sit inert from time of manufacture
  - Must be able to be used at a moment's notice
  - Must function as intended whether newly made or 30 years old
- **However, solid rocket motors**
  - Are mechanically and chemically complex
  - Are designed with very small margins
  - Change substantially with age
  - Are often required to function long beyond the design life
  - May be subjected to unexpected environments
  - Are generally not capable of maintenance/repair

Introduction (cont.)

- In order to maintain reliability and safety, entire systems will be condemned when a small percentage are considered non-viable
  - This is because there is no way to determine which individual assets are not viable
  - Surveillance programs typically test a small (not statistically meaningful) number of assets due to costs
- Solid rocket motors would appear to be an ideal (if challenging) application for Integrated Vehicle Health Monitoring

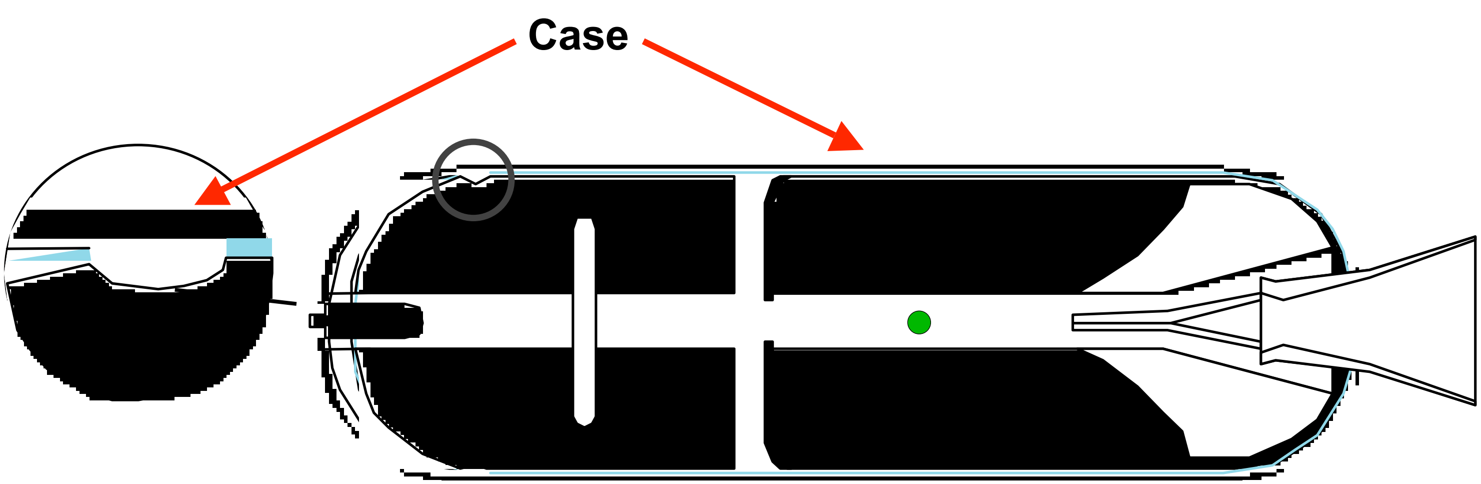
Solid Rocket Motor Structural Issues

- **Idealized Solid Rocket Motor**



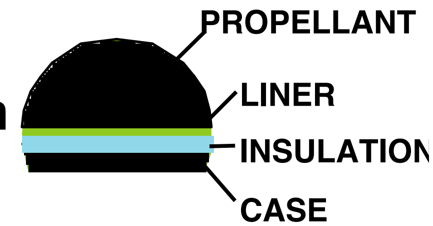
Solid Rocket Motor Structural Issues

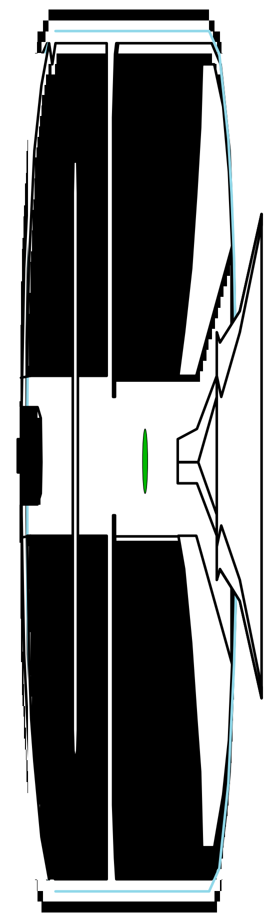
- **Cases**
  - Maintain structural integrity against motor operating pressure and dynamic/maneuvering loads
  - Often made of composite materials (Kevlar, carbon fiber, glass) due to these materials' high specific strength
  - Susceptible to barely-visible/invisible impact damage
  - Can and has led to loss of assets



Solid Rocket Motor Structural Issues

- **Propellant-Liner-Insulator System**
  - Insulator: Protects case from heat of combustion
    - Typically rubber material such as EPDM
  - Liner: Polymeric adhesive to facilitate bonding between insulation and propellant
  - Propellant: Provides energy of combustion
    - Polymeric binder containing crystalline oxidizer (typically ammonium perchlorate) and fuel (e.g. aluminum)
    - Mixed with curatives, burn rate modifiers, cast into motors, and cured
    - Resulting material is non-linear, viscoelastic, non-uniform, and prone to damage
- **Entire system is chemically active – oxidative cross-linking, bondline degradation due to moisture, mobile reactive species migration**



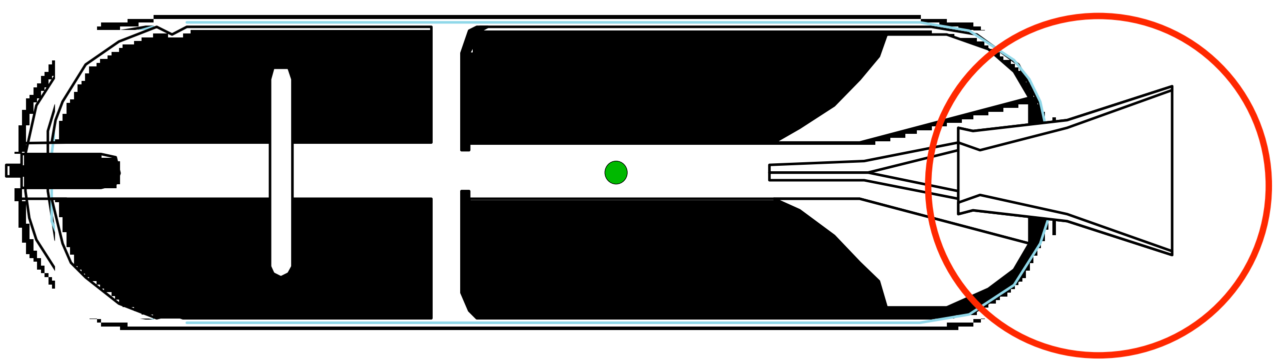


Solid Rocket Motor Structural Issues

- **Propellant-Liner-Interface System – Structural Challenges**
  - Voids and Inclusions
    - Large unintended objects or trapped air bubbles embedded in propellant
    - Changes strain field, can lead to cracking
    - Inclusions can cause anomalous burning behavior
  - Cracks and Debonds
    - Changes strain field, provides additional burning surface
    - If flame speed is faster than crack propagation speed, burning surface is the only concern
    - If crack speed is faster than flame speed, crack can propagate, providing significant additional burning surface, possible premature exposure of case to flame
    - Debonds are similar, but between propellant-liner-insulator materials

Solid Rocket Motor Structural Issues

- **Nozzles**
  - Convert thermal energy of combustion process into propulsive force
  - Typically made from composites such as carbon phenolic or carbon-carbon to further reduce weight and provide thermal resistance
  - As with the case, these materials are easily damaged
  - Multiple bonded components in nozzles that degrade with age



Implementation of Health Management on SRMs

- Current model
  - Take a small number of assets from the fleet
  - Perform verification firing on some, dissect others
  - If these are nominal, the entire fleet is considered to be viable
  - If not, following further investigation, the entire fleet may be condemned and destroyed
- While attempts are made to chose “bad” motors for inspection, asset history is rarely known well
- Small number of dissections and test firings means there is a strong probability of destroying viable assets (at great cost) or not catching bad assets, resulting in mission failure, destruction of government property, or loss of life

Use of IVHM in Strategic/Space Launch Systems

- The major health monitoring activity for current strategic motors is the Automated Non-Destructive Evaluation System (ANDES 2) at Hill Air Force Base, Utah
  - ANDES is a data analysis system evaluating computed tomography (CT)
  - Capable of inspecting motors larger than five feet in diameter, detecting voids, inclusions, debonds, or other flaws as small as 10 mils
  - ANDES identifies flaws and recommends whether they meet or violate the motor specification
- While this system is extremely capable, due to the cost of transporting assets, it is only used for initial inspections and when the motor is returned to the depot for other maintenance

Use of IVHM in Strategic/Space Launch Systems

- **Marks measured and evaluated by ANDES can be automatically converted to faceted surfaces and imported into the Structural/Ballistic Analysis System (SBAS) software**
- **SBAS performs coupled fluid-structural-ballistic-thermal of the motor**
  - **In particular, SBAS can import the ANDES flaws, determine whether and how they will propagate, and automatically do so, remeshing the model without user intervention**

Hill AFB High Resolution 3D Computed Tomography (HR3DCT) Facility Inspecting Large Steel Case Boost Motor

Use of IVHM in Strategic/Space Launch Systems

- **Other non-destructive techniques are rarely used on deployed systems**
  - Eddy current and ultrasound are sometimes used for quality control during manufacturing but not typically after fielding
  - Embedded sensors have been demonstrated on laboratory programs and subscale assets, but are not implemented on fielded systems
  - Chemical aging models have been developed, but the utility is currently limited as high-quality data can only be acquired in destructive testing of assets.
  - Chemical sensors are being developed to monitor aging of propellant-liner-insulator and interfaces, but are still quite immature for this application

Development of an Instrumented Motor

- An instrumented motor would be one with periodic surveillance, most likely with embedded sensors
  - Subscale assets with embedded sensors have been manufactured and fired
  - A critical question is the effect the sensors have on the motors
    - Long-term material compatibility
    - Embedded power and data lines
    - Strain field perturbation by the sensors
  - These questions are currently under investigation under a pair of AFRL programs called Sensor Application and Modeling

Sensor-Motor Inverse Problem

- In general, available sensors (stress, strain, chemical concentration, gross configuration) measure current state of the asset
- What is really required to predict current and future viability of a motor are inherent material properties (e.g. mechanical moduli, chemical diffusion parameters)
  - This is because the properties are constantly changing, and are often poorly known under the best of circumstances
  - Zero-time properties can vary 5-10% from motor to motor, batch-to-batch, and within individual motors
  - Environmental history, which drives the evolution of properties, is also rarely known
- Ideally, we could inspect every motor at the depot, but this is not feasible due to cost and time issues

Sensor-Motor Inverse Problem

- **The solution is to understand how a small number of well-chosen measurements can provide critical data about the global state of the motor**
- **Preliminary work has been performed by Dr. Timothy Miller at AFRL to investigate precisely this issue**
  - **Model: 5” CP motor, Steel case, .5” bore diameter, plane strain**
  - **Data acquired at model bondline, serving as a set of “virtual sensors”**
  - **Bore cracks from .25” to 1.0” in depth placed in motor**
- **Even small cracks significantly relieve the strain in the motor and break the symmetry, providing a method for detecting, localizing, and potentially measuring crack size**

Sensor-Motor Inverse Problem

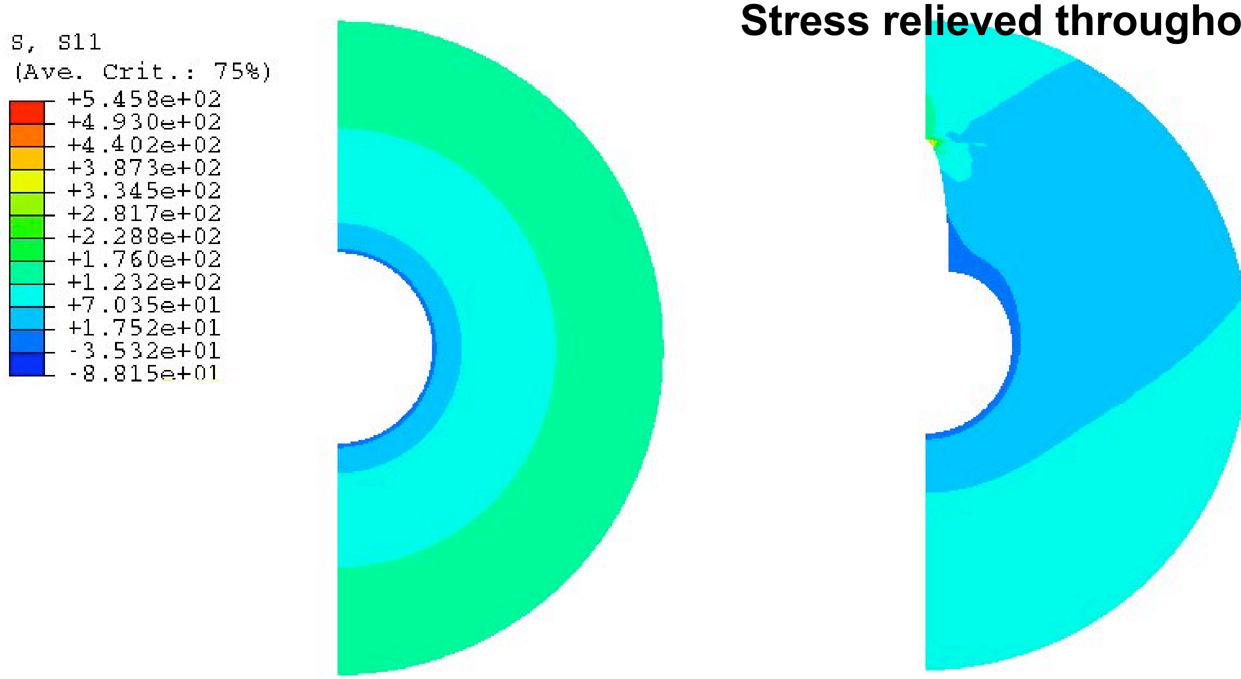
Uncracked configuration:

Radially symmetry maintained

Cracked configuration:

Radially symmetry broken

Stress relieved throughout motor



- **Depending on the sensitivity of the sensors, their placement, and their number, significant information can be acquired about the configuration of the motor with minimum impact and cost**

4-Step Approach for Deploying IVHM on SRMs

- Following is a potential model for deployment of an integrated vehicle health monitoring on solid rocket motors
- Only one of many possible approaches
- While the four components follow in a generally linear fashion, nothing requires that they be performed in order, or that all four be implemented
- In addition, for any given system, a detailed analysis must be performed to determine the payoff of such a system in light of the risks
  - IVHM must address particular needs
  - IVHM must not negatively impact the system

4-Step Approach for Deploying IVHM on SRMs

- **Step 1: Environmental Monitoring**
  - Motors are chemically complex and active
  - Aging of individual assets can vary significantly due to environmental differences over long lifetimes
  - Environmental dataloggers would provide basic, fundamental information for prediction of future state of motors on an individual basis
    - Temperature, humidity, acceleration, gaseous chemical products (for propellants with known outgassing products)
  - Particularly important for tactical motors
  - Combined with zero-time data and accurate chemical aging models, can potentially identify off-nominal motors

4-Step Approach for Deploying IVHM on SRMs

- **Step 2: External Sensors**
  - While depot inspection systems are useful, bringing assets from the field to the depot for periodic inspections is prohibitively expensive (time and cost)
  - External (non-imbedded) sensors would enable condition-based maintenance
  - Systems which can detect, localize, and make a qualitative assessment of damage to composite cases have been demonstrated using both piezoelectric and fiber optic sensors
  - Measurement of internal state of motors is significantly more difficult with external sensors
    - Portable X-ray, CT, UT could be developed, but would still be expensive to deploy on the entire fleet or to transport to silos

4-Step Approach for Deploying IVHM on SRMs

- Step 3: Internal Sensors on Surveillance Assets
  - Designate surveillance assets which would be fully instrumented with a suite of embedded sensors
  - Current aging and surveillance programs use plug motors and motor dissections to represent the health of the entire fleet
  - These assets are taken from the fleet and are assumed to be representative
  - Instrumenting these assets will
    - Provide confidence that instrumentation does not negatively affect assets
    - Add significant information for improvement of aging models for materials
  - Substantial information could be acquired with just 5-10% of the population instrumented in this manner

4-Step Approach for Deploying IVHM on SRMs

- **Step 4: Fully instrumented fleet**
  - Once program offices gain confidence in the use of IVHM, fully instrumenting the fleet becomes possible
  - Sensors must be designed into the system from the beginning—if added as an afterthought, they have the potential to do more harm than good.
  - Advanced data acquisition and diagnostic capabilities could move much of the data processing onto the missiles
  - Enables a simple “red light/green light” for the end user

Future Technology Needs

- To enable this kind of vision for health monitoring of SRMs, new technologies would be beneficial. These include (but are far from limited to)
  - Modulus sensors:
    - Stress and strain of assets are rarely of interest by themselves, but are necessary for determining the current physical properties of the asset
    - The ability to determine the current properties of the propellant-liner-insulation system enables accurate prediction of motor response
    - Ideally, a method to determine various mechanical moduli throughout the asset
  - Chemical sensors:
    - Mechanical property changes in the PLI are driven by chemical reaction-diffusion processes
    - Current chemical sensors are large and tend to cause heating of the propellant
    - Again, field measurements would be of substantial benefit

Future Technology Needs

– Data Manager:
  - Mostly requiring a change of philosophy
  - Data ownership issues
  - Maintenance of raw data, rather than processed information to allow use of future developed models
– Non-contact sensors
  - Compact, transportable systems to replace depot inspections with CT, UT, X-ray
  - External sensors to replace embedded sensors (stress, strain, chemical concentration)

Summary and Conclusions

- **Solid rocket motors could be an ideal platform for structural health monitoring, but present a number of unique challenges**
- **Significant effort has been performed to understand the behavior of SRM materials, how they age, and how that process impacts the readiness of a system**
- **Significant work remains to be performed**
  - **Development of a sensor implementation plan to maximize benefit while minimizing impact to the system**
  - **Development of advanced sensors and diagnostics to acquire necessary data for aging models non-destructively**
  - **Overcoming resistance to sticking things into mission critical systems**
- **If these can be achieved, the benefits will be great, substantially reducing cost and improving safety and readiness**